

A Dynamic Model for the Evaluation of Aircraft Engine Icing Detection and Control-Based Mitigation Strategies

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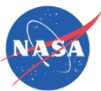
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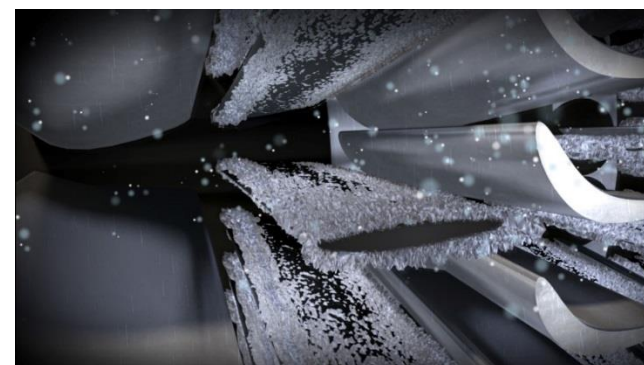
Outline

- Background:
 - The ice particle threat to engines in flight
 - A control-based approach to icing risk mitigation
- Dynamic engine model overview and features
 - Closed-loop control logic
 - Heat extraction due to ice particle ingestion
 - Flow blockage due to ice buildup in engine compression system
 - Engine actuators
- Comparison of dynamic engine model to engine ice crystal icing test cell data and manufacturer's customer deck
- Summary



The Ice Particle Threat to Engines in Flight

- Since 1990, there have been a number of jet engine powerloss events reported on aircraft operating in ice particle conditions
 - Temporary or sustained power loss, engine uncontrollability, engine shutdown
- Ice crystals enter the engine's core, melt, and accrete on engine components during flight
- Many possible causes of power loss:
 - Damage due to ice shedding
 - Flame-out due to combustor ice ingestion
 - Compressor surge
 - Sensor icing
 - Engine rollback
- Within the aviation community, research is ongoing to characterize the environmental conditions under which engine icing can occur, understand the mechanisms by which ice particles can accrete on engine components, and develop mitigation strategies.

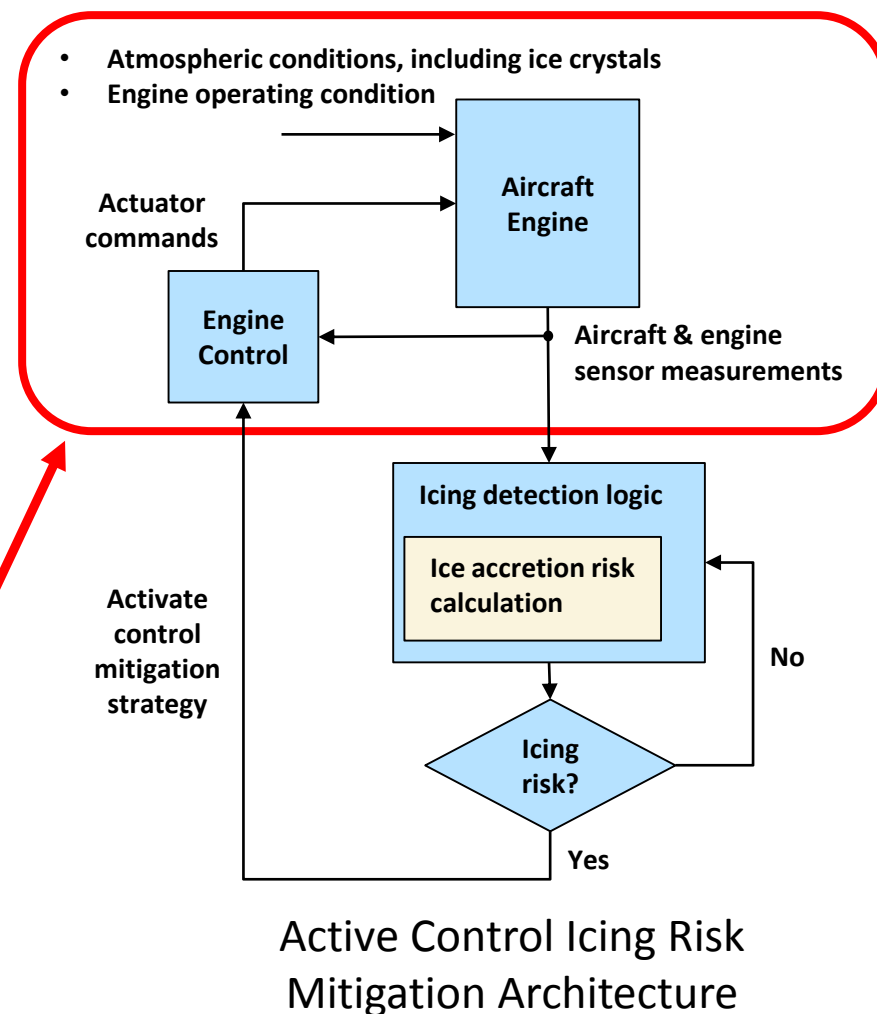


Images courtesy of NASA



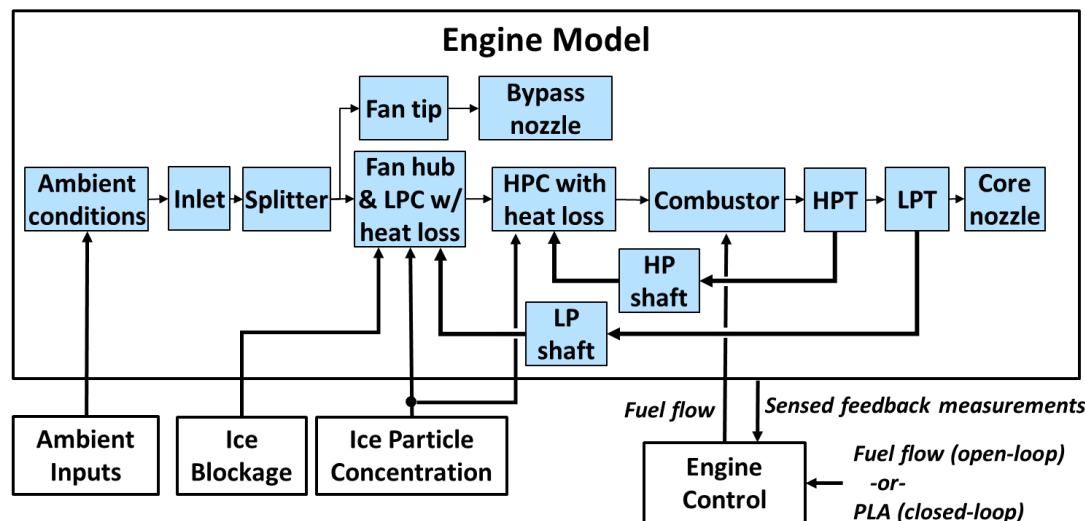
Control-Based Icing Risk Mitigation

- Potential mitigations to engine icing problem include
 - Avoidance of flight through ice crystal atmospheric conditions
 - Re-design of engine hardware
 - Ice protection systems
- Active control icing risk mitigation architecture
 - Includes detection and control-based mitigation logic
- This paper presents a dynamic aircraft engine model created for the initial development and evaluation of aircraft engine icing detection and control-based mitigation strategies.





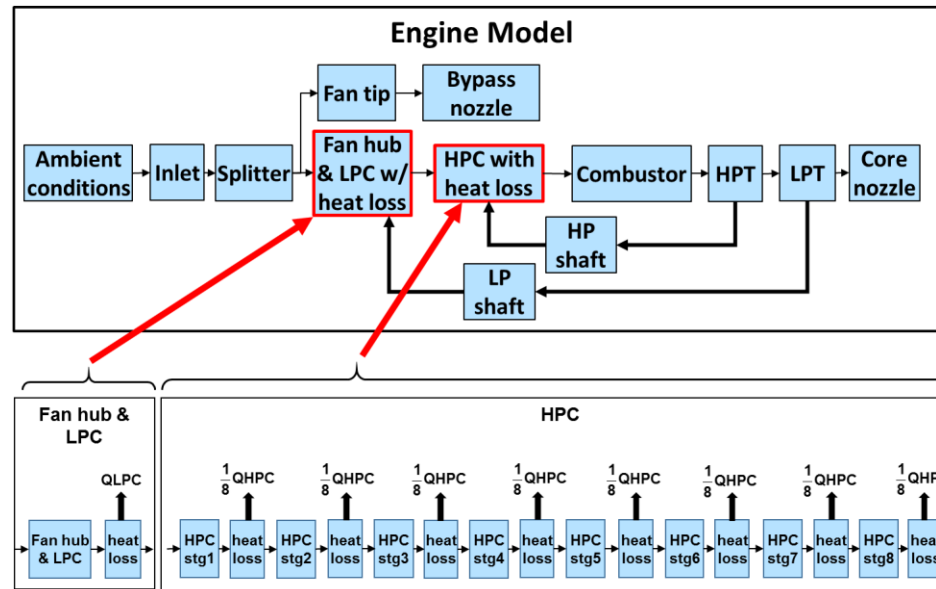
Dynamic Engine Model Overview



Engine model block diagram

- Dynamic model of Honeywell ALF502R-5 turbofan engine
 - Experimental versions of this engine underwent engine icing testing at NASA Glenn in 2013 and 2015
 - OD component level model
 - Derived from Numerical Propulsion System Simulation (NPSS) model of the ALF502R-5
 - Coded in the Matlab/Simulink environment using a NASA-developed open-source thermodynamic simulation package – Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
 - Includes performance losses caused by heat loss due to ice particle ingestion and ice blockage in the engine's compression system
 - Includes engine control logic enabling the simulation of transient engine operation

Heat Extraction Due to Ice Particle Ingestion



- Model includes heat (enthalpy) extraction effects to account for the phase transition (ice→water→vapor) that ingested ice particles undergo as they pass through the engine's compression system.
- Heat extraction is modeled to occur both within the LPC and the HPC:

$$\text{LPC heat extraction: } Q_{LPC} = w_{ice} c_{ice} (T_{melt} - T_2) + w_{ice} H_f + w_{ice} c_{water} (T_{25} - T_{melt})$$

$$\text{HPC heat extraction: } Q_{HPC} = w_{ice} c_{water} (T_{boil} - T_{25}) + w_{ice} H_v + w_{ice} c_{steam} (T_3 - T_{boil})$$

w_{ice} = ice mass flow rate

T_{melt} = ice melting temp

T_{boil} = water boiling temp

c_{water} = specific heat of water

c_{ice} = specific heat of ice

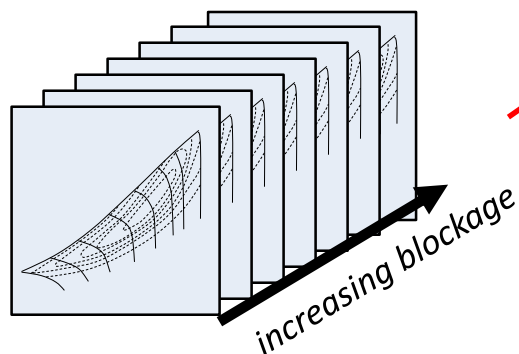
H_f = heat of fusion of ice

H_v = heat of vaporization of water

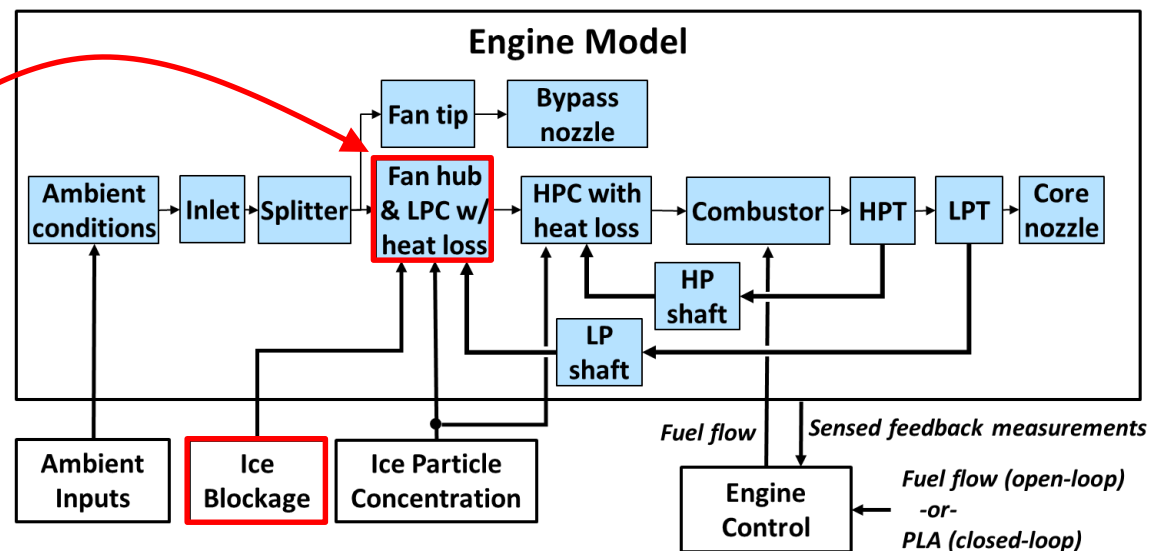


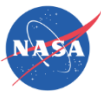
Flow Blockage Due to Ice Buildup in LPC

- Model includes an “LPC ice blockage” input, a lumped parameter that captures LPC performance changes due to ice accretion
- Captured through a series of modified LPC maps, each representing a different amount of ice blockage (maps generated from NASA-developed mean line compressor code (COMDES))
- Results in a series of maps that can be stacked and interpolated between to simulate changing levels of ice blockage



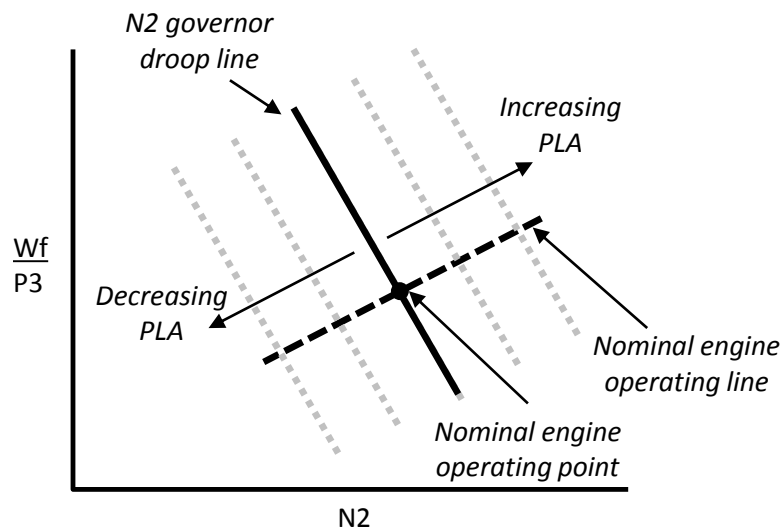
Stacked series of LPC compressor maps reflecting increasing levels of ice blockage



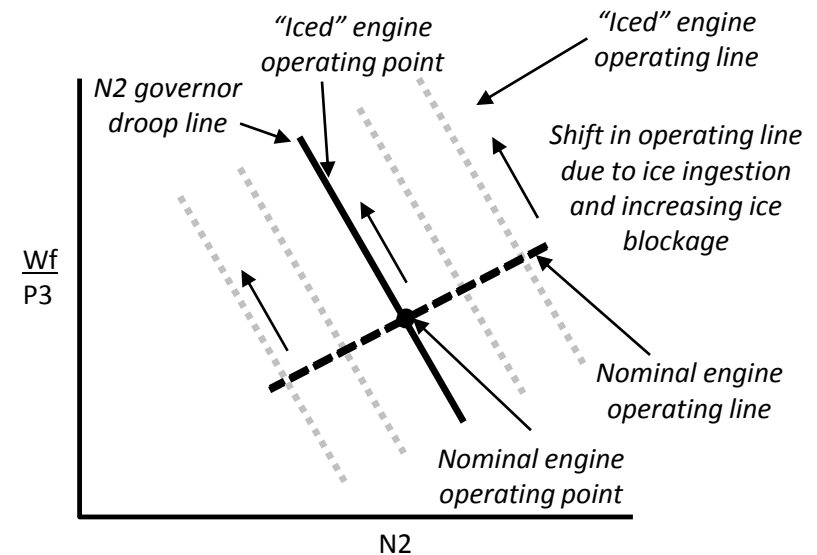


Engine Control Logic

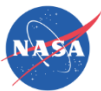
- User can operate the engine in either open-loop or closed-loop control mode
 - In open-loop operation, user supplies fuel flow input
 - In closed-loop operation, user specifies power lever angle (PLA), and engine operates on core speed (N2) governor droop line
 - Closed-loop control logic allows the model to emulate the ALF502R-5 engine's response to ice particle ingestion and ice blockage in the LPC



Movement of N2 governor droop line with changing PLA

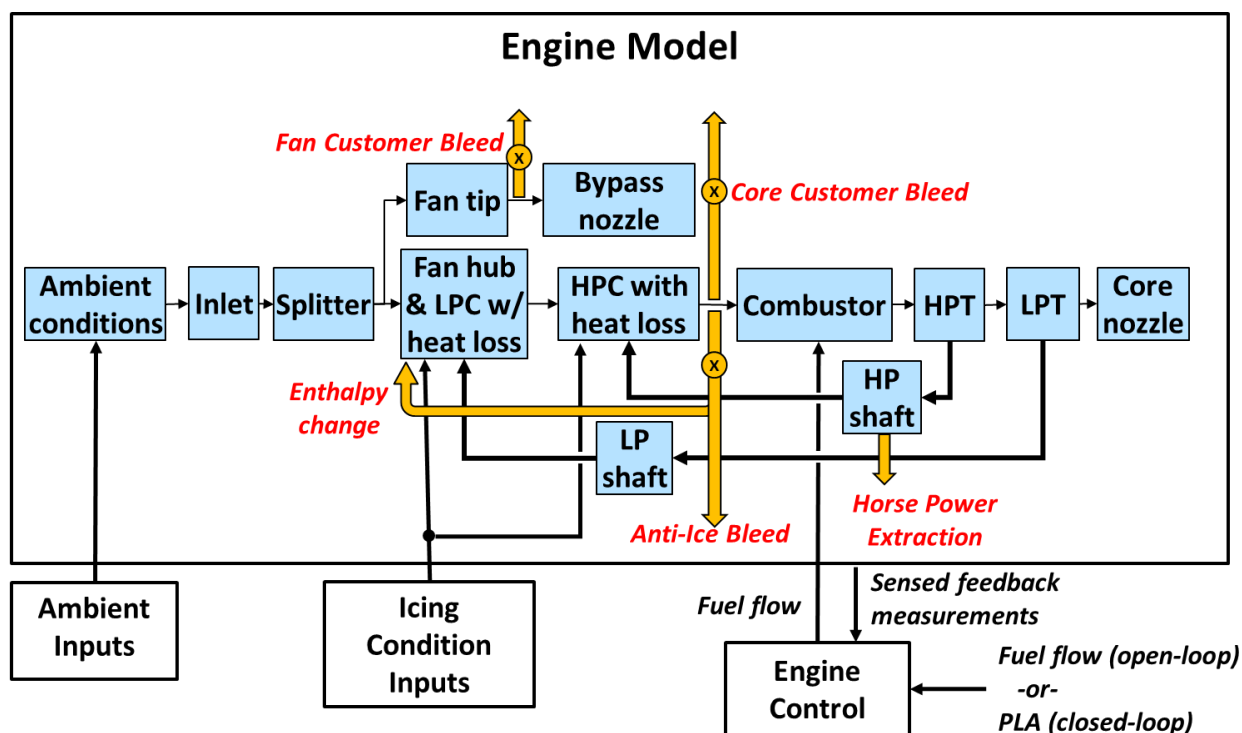


Movement of engine operating line caused by heat transfer due to ice ingestion and increasing ice blockage



Auxiliary Actuators

- Four auxiliary actuators added to model – enables future studies to assess how modulation of these actuators impacts ice accretion risk.
 - Fan customer bleed
 - Core customer bleed
 - Anti-ice bleed
 - Horsepower extraction



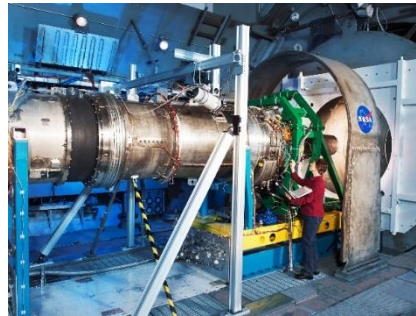


Aircraft Engine Ice Crystal Icing Testing in NASA Glenn Propulsion Systems Laboratory (PSL)

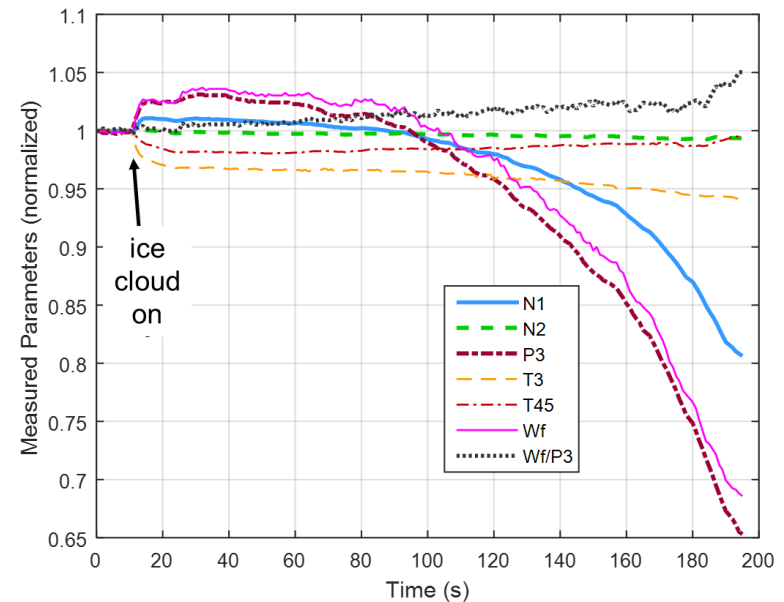
- The NASA Glenn PSL is an altitude simulation facility for experimental research on air-breathing propulsion systems
- A PSL test cell has been upgraded to include a water spray nozzle array system to produce simulated ice crystal cloud conditions
- Experimental versions of Honeywell ALF502R-5 engine underwent ice crystal icing testing in PSL in 2013 (LF01) and 2015 (LF11).



Water injection
spray bars installed
in PSL test cell



Experimental ALF502R-5
engine installed in PSL
test cell

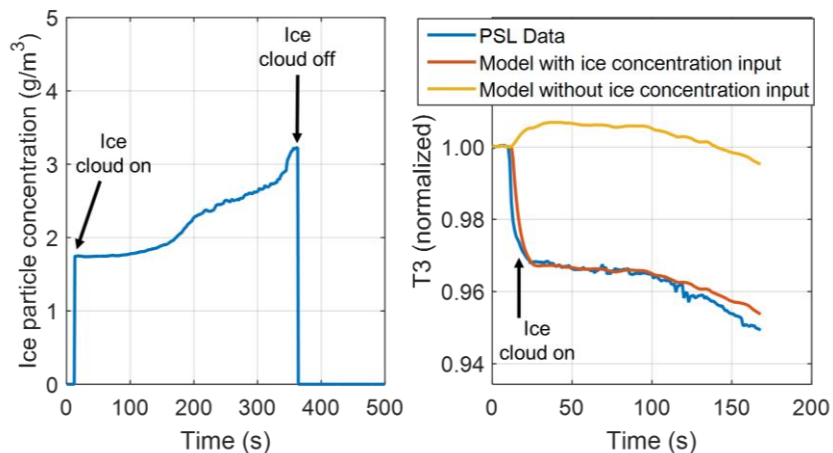


Normalized measurement parameters recorded
during uncommanded engine rollback event
caused by ice crystal icing (LF01 Run 193)



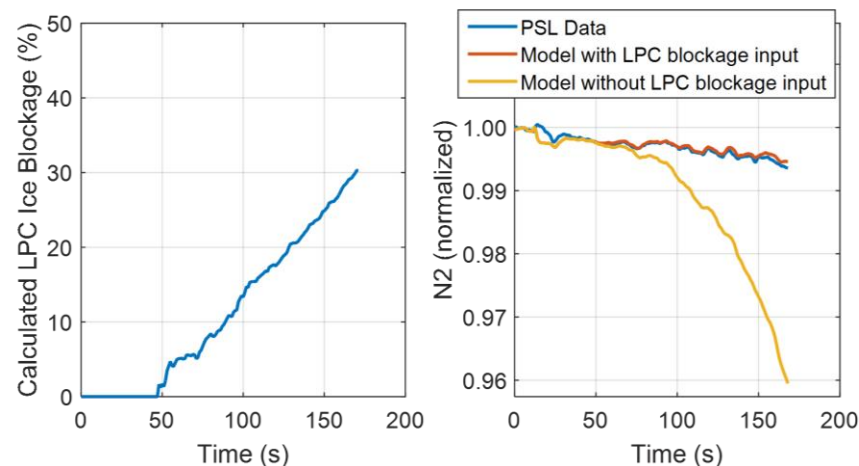
Comparison of Dynamic Engine Model to LF01 Engine Experimental Data

- Model was run under both open-loop and closed-loop control mode
 - Recorded parameters of altitude, Mach, dTamb, Wf (open-loop only), and PLA (closed-loop only) were supplied as model inputs
 - Additional model input parameters of ice particle concentration and LPC ice blockage were determined based on experimental data
 - Ice particle concentration profile is calculated as a function of measured spray bar water flow rate and engine volumetric flow rate, with scale factor adjustment to produce a comparable temperature drop as that observed in recorded HPC exit temperature (T3)
 - The percentage of LPC ice blockage was not measurable during the test. Model input of this parameter was selected to match measured engine core speed (N2) response.



a) Calculated ice particle concentration b) Engine and model T3 response

Calculated ice particle concentration and T3 response during LF01 Run 193 rollback event



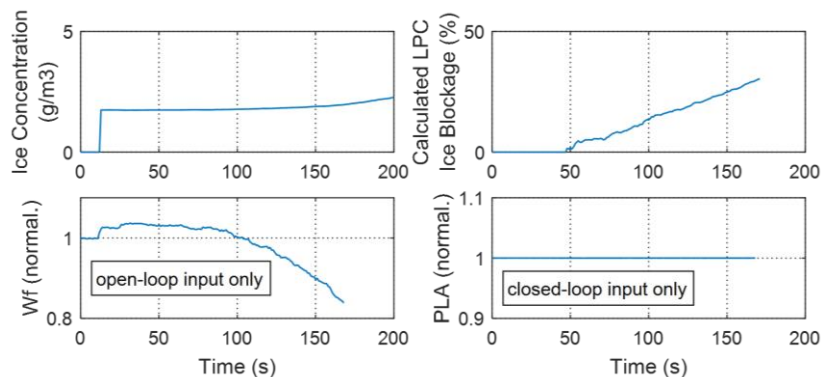
a) Calculated LPC ice blockage b) Engine and model N2 response

Calculated LPC ice blockage and N2 response during LF01 Run 193 rollback event



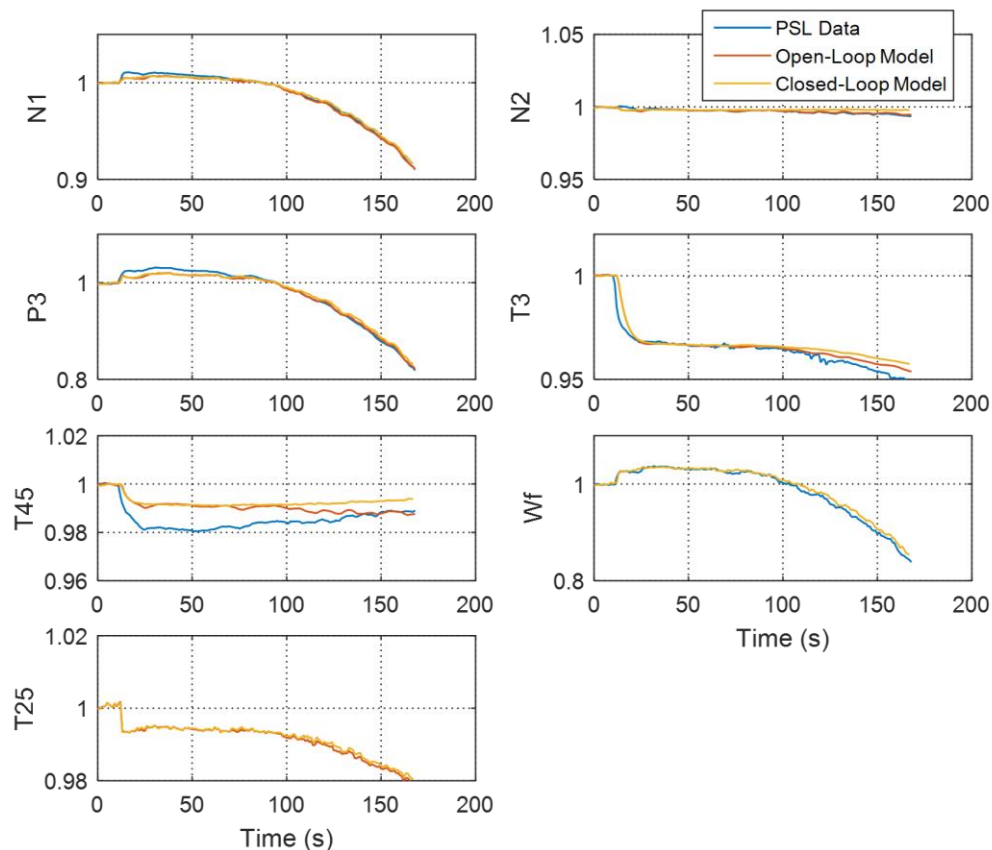
Modeling of LF01 Run 193 Engine Rollback Event

- Run 193 rollback event was simulated by running the dynamic engine model in both open-loop and closed-loop control mode
- Flight condition for Run 193 was 28K feet, 0.5 Mach, and ISA +28°F



Model Input Parameters (in addition to Alt, Mach, and dTamb)

- Ice concentration
- % ice blockage
- Fuel flow (W_f): *open-loop only*
- Power lever angle (PLA): *closed-loop only*



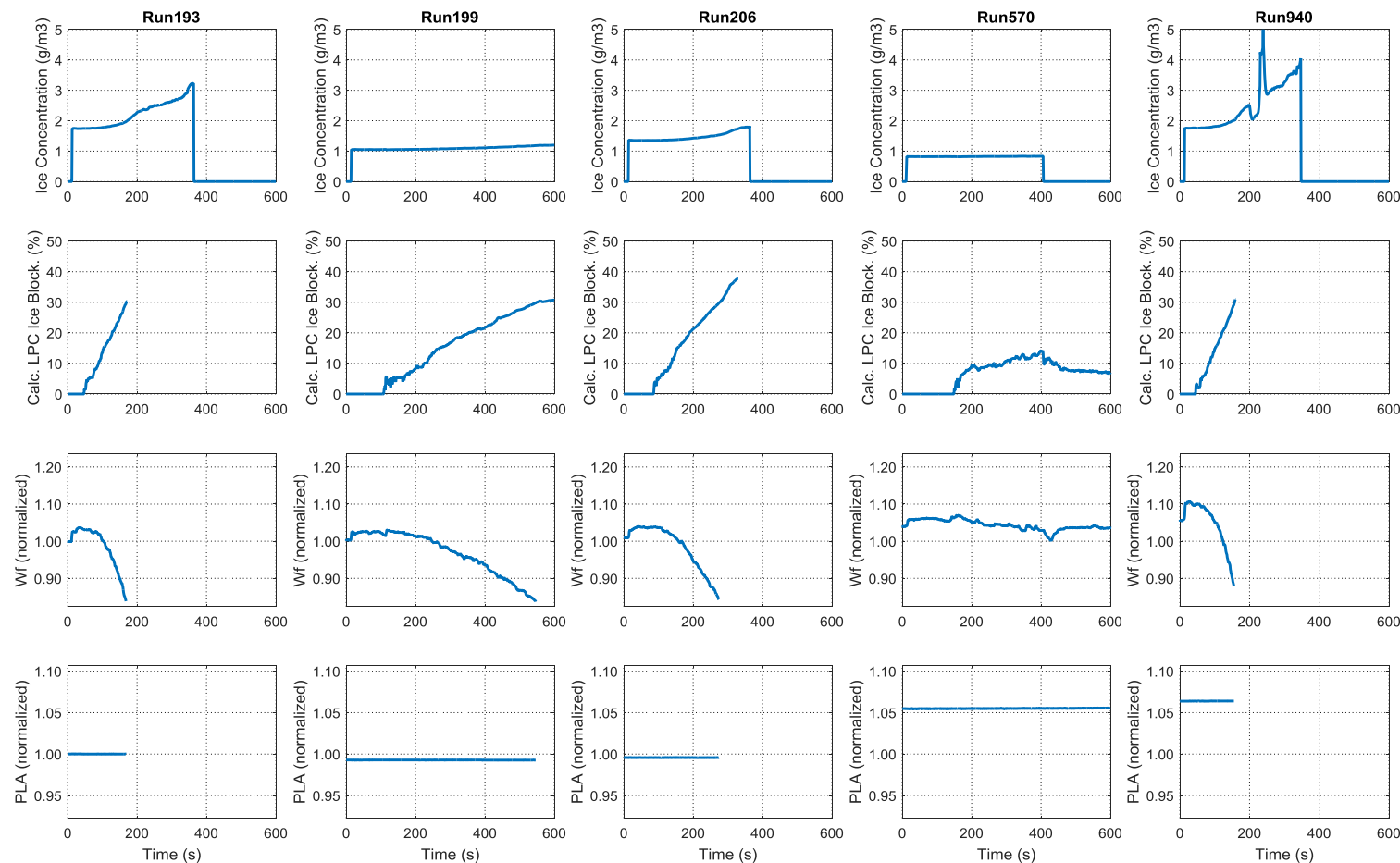
Normalized Engine and Model Output Parameters

- Fan speed (N_1)
- Core speed (N_2)
- HPC exit pressure (P_3)
- HPC exit temp (T_3)
- Exhaust gas temp (T_{45})
- Fuel flow (W_f)
- LPC exit temp (T_{25})

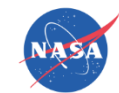


Modeling of Additional LF01 Engine Rollback Events

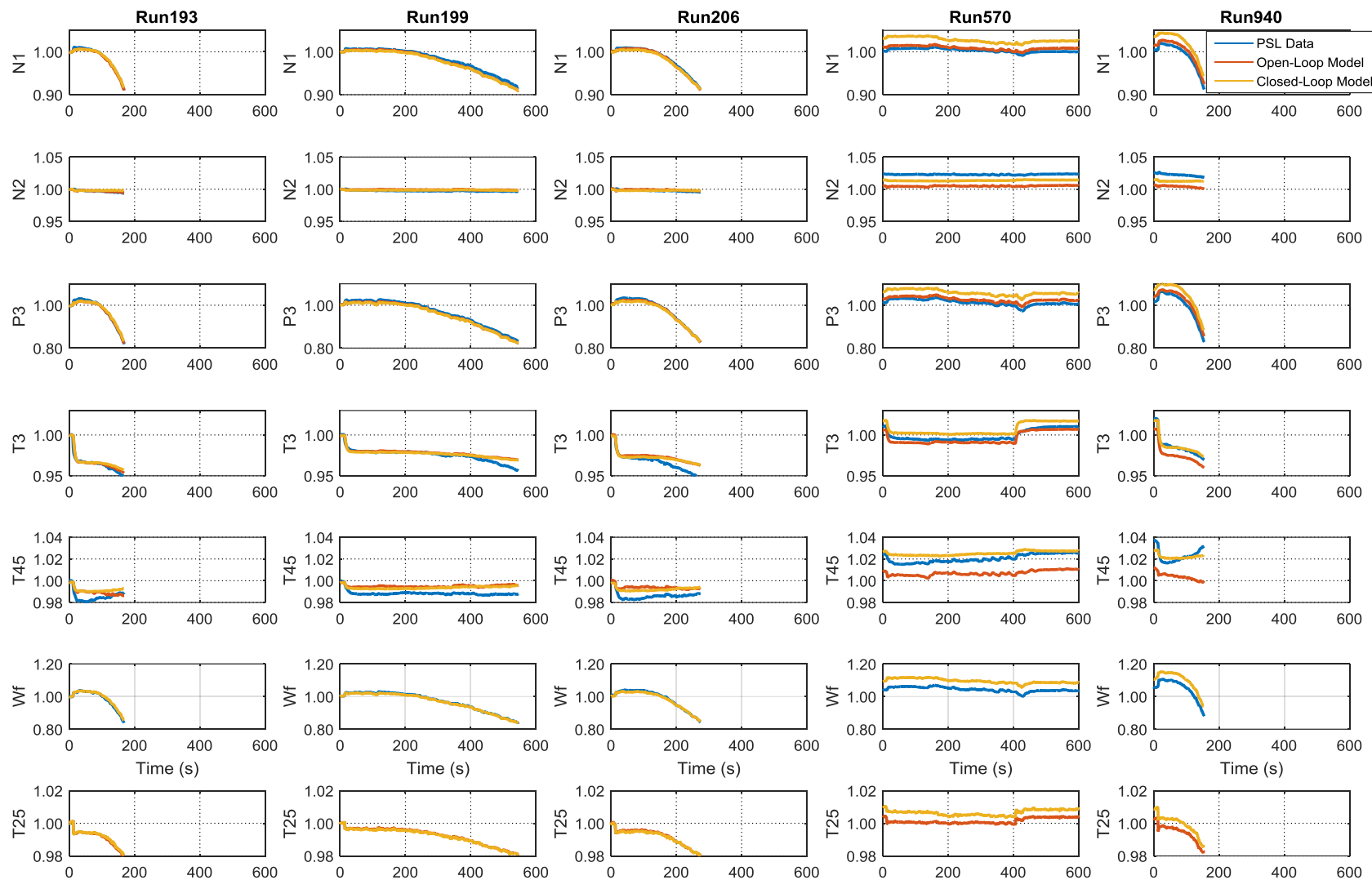
- In addition to Run 193, four additional LF01 test runs (Run 199, Run 206, Run 570 and Run 940) were selected for comparison against the model
- Input parameters for these runs are shown below



Model Input Parameters



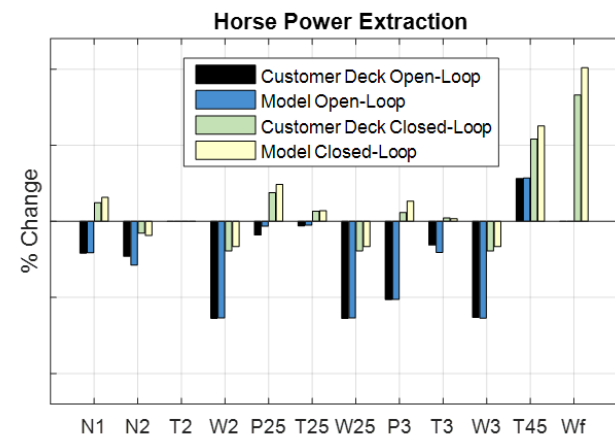
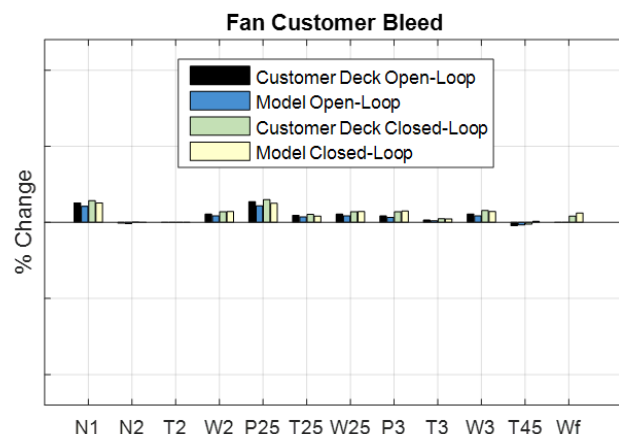
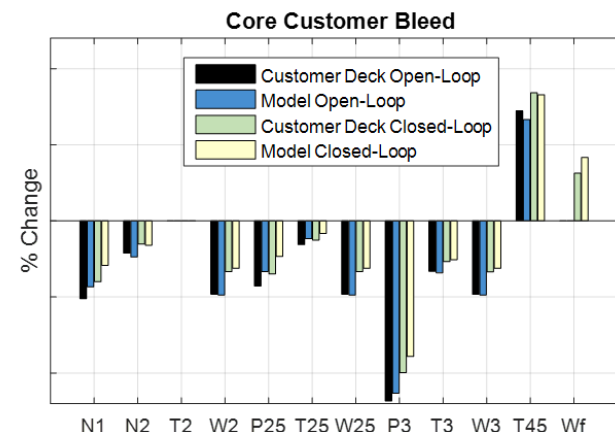
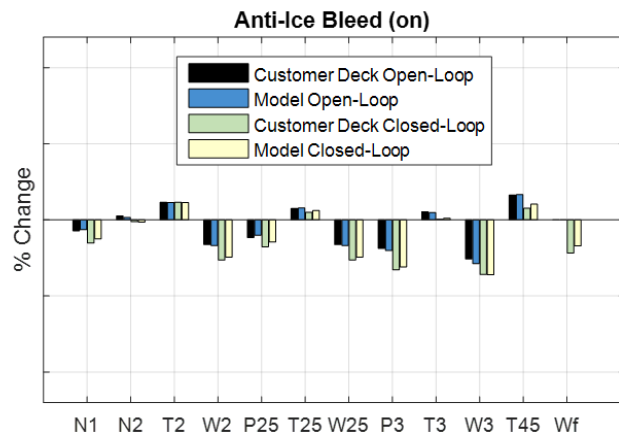
Modeling of Additional LF01 Engine Rollback Events (cont.)



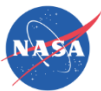
Model Output Parameters

Comparison of Engine Model to Customer Deck

- In follow-on studies, the developed engine model will be used to evaluate the feasibility of control-based strategies for mitigating the risk of engine icing. This will entail modulation of the model's auxiliary actuators and assessing the corresponding impact on icing risk.
- The manufacturer's steady-state customer deck was used to assess correct implementation of auxiliary actuators within the model.

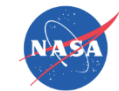


Comparison of Model and Customer Deck Steady-State Response to Actuator Modulation



Summary

- A dynamic model of the ALF502-5R turbofan engine has been developed and evaluated
- Model was shown to emulate engine system-level behavior during ice crystal icing test cell evaluations as well as the steady-state outputs produced by the manufacturer's customer deck
- Key features of the model include
 - Closed-loop controller allowing the simulation of engine transients
 - Heat extraction effects reflecting the heat loss the engine experiences as ingested ice crystals melt and vaporize in its compression system
 - Flow blockage effects reflecting the buildup of ice in the engine's low pressure compressor
 - Auxiliary actuators enabling the modulation of engine performance
- Potential follow-on work
 - The model can be used in follow-on studies to develop and evaluate potential icing risk detection and control-based mitigation strategies



Acknowledgments

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